

Elastic properties of highly anisotropic thin poly(propylene) foams

Enis Tuncer^{*} and Michael Wegener

*Applied Condensed-Matter Physics, Department of Physics, University of
Potsdam, D-14469 Potsdam, Germany*

Abstract

In this letter, elastic properties of highly anisotropic cellular poly(propylene) films are reported. The material shows peculiar elastic properties compared to other foams in the literature. The data is displayed as the relative Young's modulus E^*/E_s versus relative density ρ^*/ρ_s . Almost all the data from the literature are located on the region $E^*/E_s = (\rho^*/\rho_s)^n$ with $1 \leq n \leq 6$. The introduced material on the other hand have lower relative Young's modulus at high relative densities, $n \geq 6$.

Key words: Foams, cellular materials, homogenization, elastic properties, Young's modulus

Foams are solid-gas mixtures, in which the solid phase forms a continuous (percolating) network structure, and performs an action depending on the application, *i.e.*, supports load, conducts heat/electricity, *etc.* The ratio of effective Young's modulus of foams to the solid's modulus E^*/E_s has been related to the volume fraction of the solid material ρ^*/ρ_s [1].

$$E^*/E_s = C (\rho^*/\rho_s)^n \quad (1)$$

where C and n are constants and superscript '*' and subscript 's' denote the properties of the effective and the solid material, respectively. Yet, there is no unique theory that explains the effective properties of foams or any composite that takes into account the geometrical parameters of the material. However, equations based on the effective medium theory and empirical mixture formulas have been proposed [2, 3]. For foams Eq. (1) has been extensively used, and the constant n often gives information about the structure of material in hand [1, 4, 5, 6, 7].

^{*} Corresponding author.

Email address: enis.tuncer@physics.org (Enis Tuncer).

In Table 1, data taken from the literature for various foams and characteristic exponent values of Eq. (1) are presented. In the table, closed cell foams have the lowest exponent n which is around $\approx 3/2$ [1, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. Numerical simulations performed by considering three-dimensional closed-cell structures also yield similar exponents [4, 6]. In contrast to closed cell foams, most of the open cell foams result in $E^*/E_s \propto (\rho^*/\rho_s)^2$ dependence [1, 5, 16, 21, 22, 23, 24, 25, 26, 27]. There are some exceptions which show $n > 5/2$ dependence [4, 23, 28, 29, 30, 31], which, we believe in principle, could be due to the anisotropy in materials.

The data from the given literature in Table 1 are illustrated in Fig. 1. In the figure, the gray-region contains all the data presented in the literature (Table 1). Some of the newly published data are shown with symbols; (*) [19], (\triangle) [18], (\star) and (\blacklozenge) [23], (\blacktriangleleft) [16], (+) [20], (\bullet) [17], (\boxplus) [32], (\boxminus) [33] and (\odot) [34]. The data presented in this study are poly(propylene) foams and are plotted with (\square); our data with errorbars and other performed experiments [35]. The dashed lines (- - -) shows Eq. (1) for $C = 1$ and $n = \{1, 2, 5/2, 6\}$. All the data from the literature are located between $n \approx 1$ and $n \approx 6$ region. The solid lines (—) in the figure are calculated for a truss-like structure using the finite element method [36], which has voids as in the form of lozenge, with various void sizes, $a/b = \{1, 2, 4, 8\}$. The parameters a and b define the void dimensions in the x - and y -dimensions, respectively—when the ratio a/b is large the structure is highly anisotropic. At high concentrations of solid, the computer model based on the finite element method yield similar values as the experiments for $4 < a/b < 8$.

The original films in this study were cellular poly(propylene) with typical thicknesses around 30 – 100 μm . They were stretched by the manufacturer (VTT Processes, Finland)[37] and the lateral dimensions were much larger than the thickness of the samples. The structure of samples resembles the puff pastry, some scanning electron micrographs have been presented in Ref. [35, 36, 38, 39]. The surface area of samples are larger than 1 cm^2 for our electromechanical applications. The average void structure is oblate with dimensions around ~ 50 μm long and ~ 10 μm high from the scanning electron micro-graphs, which indicates that there are at least 5 voids in the thickness direction. The original films were inflated with a post-processing procedure [35]. Their elastic properties were measured after each inflation process with the dielectric spectroscopy method [40]. The inflation influences the relative density and average void (cell) dimension of the films. The change in the relative Young's moduli of the films is illustrated in the figure with open symbols. The relative Young's modulus and density were calculated by using $E_s = 1$ GPa and $\rho_s = 1$ g/cm^3 for the solid poly(propylene). The letters A, B and C present the different stages in the inflation process. The non-inflated films had the highest Young's moduli (A). By inflating the samples, the stiffness of the films lowered down to $E^*/E_s \approx 10^{-3}$ (B). After this point,

a further inflation of the films resulted an increase in the stiffness (C). This was due to the shape of the voids, which became nearly-isotropic. The voids become rounder with $a/b \leq 4$ —the anisotropy in the films were destroyed by the inflation. The numerical simulations utilizing the finite element method by means of simple truss-like structure [36] has showed a similar behavior (even simulations with more realistic geometries yield similar results [7]), and has verified the experimental observations. The ‘U’-shaped behavior of our data could be explained by the solid materials’ cell-wall thickness [7, 36]. It should be mentioned that if the layered texture is exchanged to a fibrous one, one might obtain much softer materials with exponents $n > 6$ in Eq. (1).

Almost all of our measurement points (only two of the data points fall in the region marked by $1 < n < 6$) are outside the region for the conventional foams. So we can conclude that as the films become more isotropic ($a/b \leq 2$), they yield similar Young’s modulus behavior as the foams presented in the literature, $n \leq 6$ in Eq. (1). Although in the literature it is not clearly stated that foams with higher characteristic exponents in Eq. (1) are anisotropic, our observations affirm that anisotropic foams yield high exponent values for the power-law expression in Eq. (1).

Finally, as a concluding remark, although poly(propylene) foam is widely used and has been known for decades, the presented low stiffness character of highly anisotropic materials at high relative densities can be advantages and preferably selected for special applications in which a multifunctional material with soft elastic properties is needed. The solid phase in that case is utilized to possess an additional feature, such as storing charge, heat, magnetic/electric polarization *etc.* A discrete example is electret materials used in transducer applications [41, 42]. The solid phase in cellular electrets is used to store electrical charge, for this reason, in order to have high charge densities, high volume fraction of solid is simultaneously desired together with low elastic constants. In addition, one can even tailor the elastic properties by using post processing techniques to change the micro-structure of the material.

References

- [1] L. J. Gibson, M. Ashby, Cellular Solids: structure & properties, 2nd Edition, Solid state science, Cambridge University Press, UK, 1997.
- [2] S. Torquato, Random Heterogeneous Materials: Microstructure and macroscopic properties, Vol. 16, Springer-Verlag, Berlin, 2001.
- [3] G. W. Milton, The Theory of Composites, Vol. 6 of Cambridge monographs on applied and computational mathematics, Cambridge University Press, Cambridge UK, 2002.
- [4] A. P. Roberts, E. J. Garboczi, Computation of the linear elastic properties

Table 1

Effective Young's modulus relative density relation for different structures, Eq. (1).

$1 < n < 2$	$3/2 < n < 5/2$	$n > 5/2$
Closed-cell	Open-cells	Anisotropic-cells(?)
Foamed glasses [8, 9, 10]	Metal foams [1, 21, 22, 23, 24, 25]	Aerogels [28, 29]
Polymer foams [11, 12, 13, 15, 16]	Polymer foams [16, 26, 27, 32, 33]	Honeycomb[23]
Metal foams [17, 34]	Numerical [5]	Penrose network[23]
Composite food [14, 18]		Various foams[30]
Biological materials [1, 19, 20]		Numerical [4, 31]
Numerical [4, 6]		

of random porous materials with a wide variety of microstructure, Proc. Royal Society 458 (2021) (2002) 1033–1054.

- [5] A. P. Roberts, E. J. Garboczi, Elastic properties of model random three-dimensional opel-cell solids, Journal of the Mechanics and Physics of Solids 50 (1) (2002) 33–55.
- [6] A. P. Roberts, E. J. Garboczi, Elastic moduli of model random three-dimensional closed-cell cellular solids, Acta Materialia 49 (2001) 187–197.
- [7] E. Tuncer, Effective elastic properties of two cellular structures in two-dimensions, [arXiv:cond-mat/0404166](#) (2004).
- [8] J. S. Morgan, J. L. Wood, R. C. Brandt, Cell-size effects on the strength of foamed glasses, Materials Science and Engineering 47 (1) (1981) 37.
- [9] J. G. Zwissler, M. A. Adams, in: R. C. Brandt, A. G. Evans, D. P. H. Hasselman, F. F. Lange (Eds.), Fracture mechanics of ceramics, Vol. 6, Plenum Press, NY USA, 1983, p. 211.
- [10] J. B. Walsh, W. F. Brace, A. W. England, Effect of porosity on compressibility of glass, Journal of American Ceramic Society 48 (12) (1965) 605–608.
- [11] N. J. Mills, H. X. Zhu, The high strain compression of closed-cell polymer foams, Journal of Mechanics and Physics of Solids 47 (1999) 669.
- [12] S. Baxter, T. T. Jones, Physical properties of foamed plastics and their dependence on structure, Plastics and Polymers 40 (146) (1972) 69.
- [13] E. Q. Clutton, G. N. Rice, in: 34th Annual Technical Conference Proceedings, RAPRA Technology, Strewsbury, 1999, p. 99.
- [14] M. G. Scanlon, M. C. Zghal, Bread properties and crumb structure, Food Research International 34 (2001) 841–864.
- [15] R. M. Christensen, Mechanics of low density materials, Journal of Mechanics and Physics of Solids 34 (6) (1986) 563–578.
- [16] H. Sun, G. S. Sur, J. E. Mark, Microcellular foams from polyethersulfone and polyphenylsulfone: Preparation and mechanical properties, European Polymer Journal 38 (2002) 2373–2381.
- [17] K. Kitazono, E. Sato, K. Kuribayashi, Application of the mean-field ap-

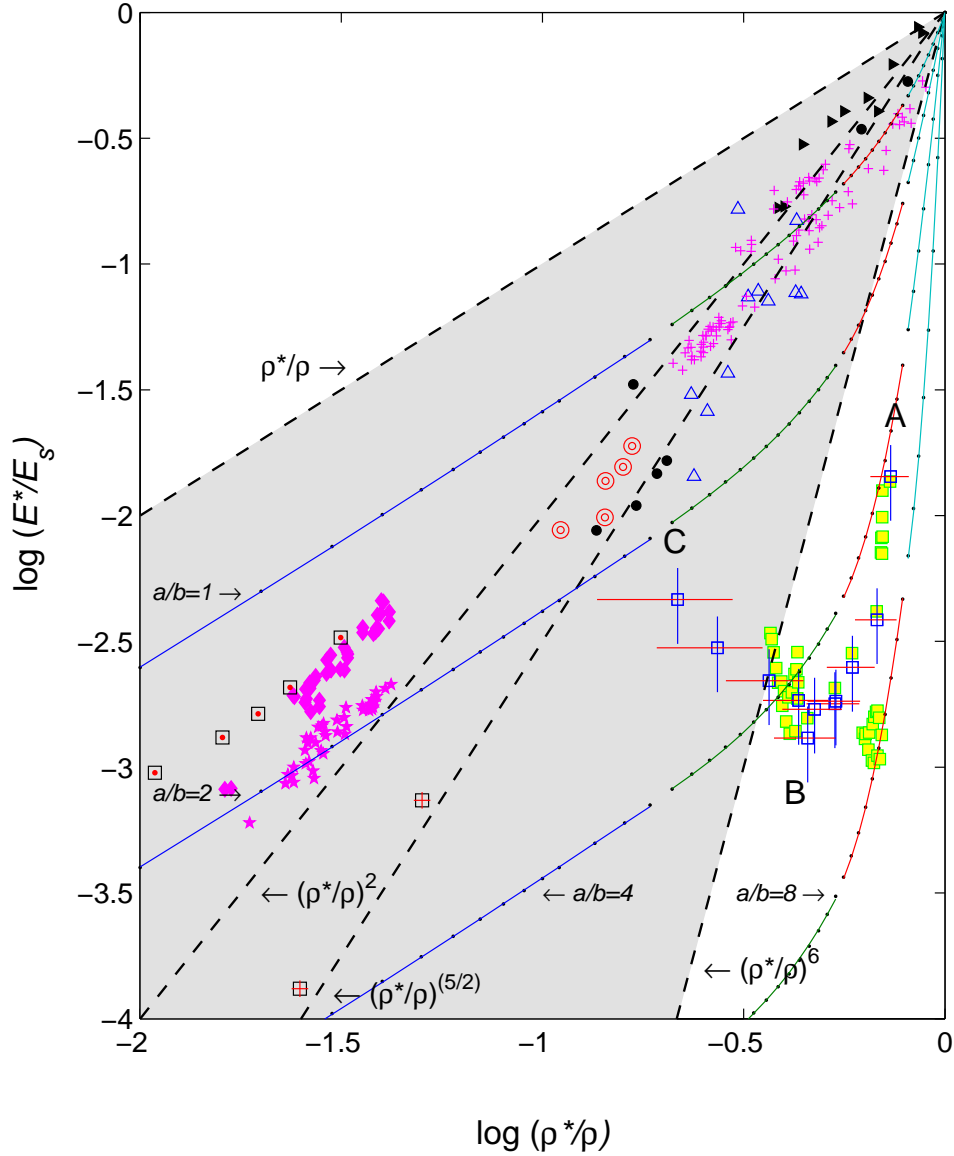


Fig. 1. Relative effective Young's modulus versus relative density for different foams. The gray region marks the area of currently available data present in the literature, Table 1. Some of the newly published data are shown with symbols; (*) [19], (Δ) [18], (\star) and (\blacklozenge) [23], (\blacktriangleleft) [16], (+) [20], (\bullet) [17], (\boxplus) [32], (\square) [33] and (\odot) [34]. The introduced and discussed poly(propylene) materials are plotted with (\square) [35] and (\square) with errorbars.

proximation to the elastic-plastic behavior for closed-cell metal foams, *Acta Materialia* 51 (2003) 4823–4836.

- [18] A. Baltsavias, A. Jurgens, T. van Vliet, Properties of short-dough biscuits in relation to structure, *Journal of Cereal Science* 29 (1999) 245–255.
- [19] A. J. C. Ladd, J. H. Kinney, Deformation and failure in cellular materials, *Physical Review E* 55 (3) (1997) 3271–3275.
- [20] C. Hellmich, F.-J. Ulm, Are mineralized tissues open crystal foams rein-

- forces by crosslinked collagen?—some energy arguments, *Journal of Biomechanics* 35 (2003) 1199–1212.
- [21] H. Hagiwara, D. J. Green, Elastic behavior of open-cell alumina, *Journal of American Ceramics Society* 70 (1987) 811–815.
 - [22] F. Han, H. Cheng, J. Wang, Q. Wang, Effect of pore combination on the mechanical properties of an open cell aluminum foam, *Scripta Materialia* 50 (2004) 13–17.
 - [23] X. Badiche, S. Forest, T. Guibert, Y. Bienvenu, J.-D. Bartout, P. Ienny, M. Croset, H. Bernet, Mechanical properties and non-homogeneous deformation of open-cell nickel foams; application of the mechanics and cellular solids and of porous materials, *Material Science and Engineering A* 289 (2000) 276–288.
 - [24] W. E. Warren, A. M. Kraynik, The linear elastic properties of open-cell foams, *Journal of Applied Mechanics* 55 (2) (1988) 341–346.
 - [25] M. J. Silva, L. J. Gibson, The effect of non-periodic microstructure and defects on the compressive strength of two-dimensional cellular solids, *International Journal of Mechanical Sciences* 39 (5) (1997) 549–563.
 - [26] J. M. Lederman, The prediction of the tensile properties of flexible foams, *Journal of Applied Polymer Science* 15 (1971) 693–703.
 - [27] A. N. Gent, A. G. Thomas, The deformation of foamed elastic materials, *Journal of Applied Polymer Science* 1 (1959) 107.
 - [28] J. Gross, G. W. Scherer, C. T. Alviso, R. W. Pekala, Elastic properties of crosslinked resorcinol-formaldehyde gels and aerogels, *Journal of Non-crystalline Solids* 211 (1997) 132–142.
 - [29] R. W. Pekala, C. T. Alviso, J. D. LeMay, Organic aerogels microstructural dependence of mechanical properties in compression, *Journal of Non-crystalline Solids* 125 (1990) 61–75.
 - [30] Z. Lui, M. G. Scanlon, Scaling young’s modulus of cellular solids, *Journal of Material Science Letters* 22 (2003) 547–548.
 - [31] A. Fazekas, R. Dendievel, L. Salvo, Y. Bréchet, Effect of microstructural topology upon stiffness and strength of 2d cellular structures, *International Journal of Mechanical Sciences* 44 (2002) 2047–2066.
 - [32] J.-P. Lee, K.-H. Lee, H.-K. Song, Manufacture of biodegradable packaging foams from agar by freeze-drying, *Journal of Materials Science* 32 (21) (1997) 5825–5832.
 - [33] N. Chan, K. E. Evans, Microscopic examination of the microstructure and deformation of conventional and auxetic foams, *Journal of Materials Science* 32 (11) (1997) 2797–2809.
 - [34] T. J. Lu, J. M. Ong, Characterization of close-celled cellular aluminum alloys, *Journal of Materials Science* 36 (11) (2001) 2773–2786.
 - [35] M. Wegener, W. Wirges, R. Gerhard-Multhaupt, M. Dansachmüller, R. Schwödiauer, S. Bauer-Gogonea, S. Bauer, M. Pääjärvi, H. Minkkinen, J. Raukola, Controlled inflation of voids in cellular polymer ferroelectrets: Optimizing electromechanical transducer properties, *Applied Physics Letters* 84 (2004) 392–394.

- [36] E. Tuncer, M. Wegener, Elastic properties of cellular polypropylene films: Finite element simulations and their comparison with experiments, [arXiv:cond-mat/0404165](#) (2004).
- [37] M. Paaajanen, J. Lekkala, K. Kirjavainen, ElectroMechanical film (EMFi)—a new multipurpose electret material, *Sensors and Actuators* 84 (2000) 95–102.
- [38] M. Wegener, W. Wirges, R. Gerhard-Multhaupt, M. Paaajanen, H. Minkinen, J. Raukola, Enhancing the cellular structure and the electromechanical response of ferroelectrets—gas diffusion expansion of voided polypropylene films, in: 2003 Annual Report, Conference on Electrical Insulation and Dielectric Phenomena CEIDP, IEEE Dielectrics and Electrical Insulation Society, 2003, pp. 36–39.
- [39] M. Wegener, W. Wirges, J. Fohlmeister, B. Tiersch, R. Gerhard-Multhaupt, Two-step inflation of cellular polypropylene films: void-thickness increase and enhanced electromechanical properties, *Journal of Physics D: Applied Physics* 37 (4) (2004) 623–627.
- [40] A. Mellinger, Dielectric resonance spectroscopy: a versatile tool in the quest for better piezoelectric polymers, *IEEE Transactions on Dielectrics and Electrical Insulation* 10 (5) (2003) 842–861.
- [41] R. Gerhard-Multhaupt, Less can be more: Holes in polymers lead to a new paradigm of piezoelectric materials for electret transducers, *IEEE Transactions on Dielectrics and Electrical Insulation* 9 (5) (2002) 850–859.
- [42] S. Bauer, R. Gerhard-Multhaupt, G. Sessler, Ferroelectrets: Soft electroactive foams for transducers, *Physics Today*.